Workshop report

Indoor microbiomes and healthy buildings: rethinking the future of indoor health

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Workshop report

Indoor microbiomes and healthy buildings: rethinking the future of indoor health

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About

The workshop **Indoor Microbiomes and Healthy Buildings: Rethinking the Future of Indoor Health**, held on 19 May 2026 at Nexus, University of Leeds (hybrid format), brought together more than 40 participants from engineering, architecture, environmental sciences, microbiology, public health, data science and related disciplines. The inclusion of online participation broadened engagement beyond the local academic community, facilitating international dialogue and strengthening opportunities for future interdisciplinary collaboration.

A key outcome of the discussions was a shift in perspective from viewing buildings as passive structures to recognizing them as dynamic socio-ecological systems, in which microbial communities interact continuously with occupants, materials, environmental conditions and behaviors. This systems-based framing was consistently reflected across both invited talks and group discussions.

The workshop situates indoor microbiomes within a broader system-based and socio-ecological framework, recognizing that human health, animal health, environmental processes and built infrastructure are tightly coupled. This perspective highlights the need to move beyond siloed approaches and towards integrated socio-ecological models of buildings. The relationships between these elements are illustrated in **Figure 1**, which presents a systems-level framework linking indoor microbiomes, building design, human behavior, environmental drivers and health outcomes. The principal thematic areas discussed during the workshop and the interconnections between them are illustrated in **Figure 2**, which provides an overview of the workshop's interdisciplinary scope.

The workshop therefore positioned indoor microbiome research at the intersection of One Health, environmental sustainability and built environment design highlighting its growing importance in addressing complex global challenges such as climate change, urbanization and health inequalities. Together, these perspectives emphasize the need for integrated, interdisciplinary approaches to understanding and designing indoor environments that support both human and microbial health.

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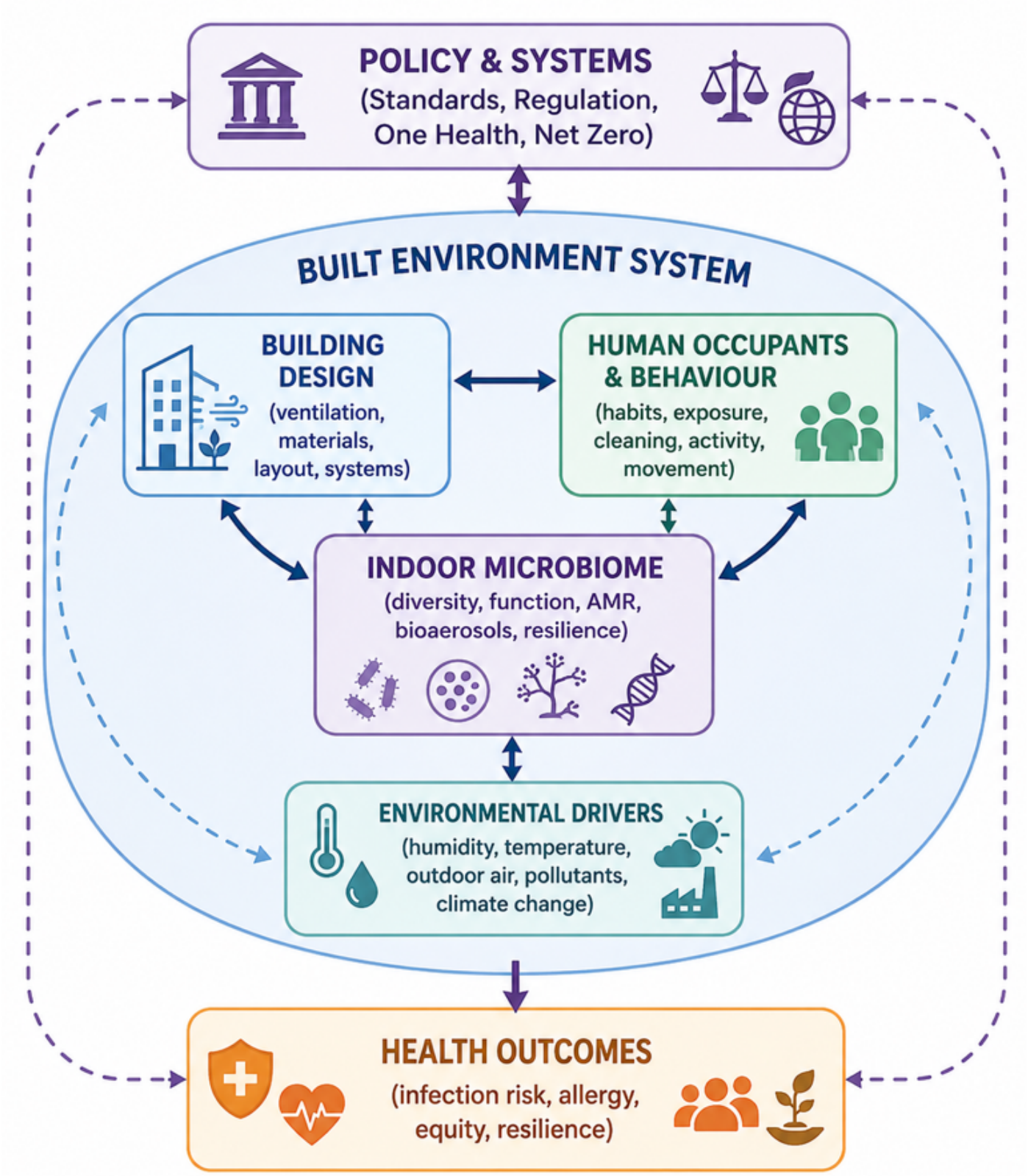

Figure 1: Conceptual framework of indoor microbiomes as a socio-ecological system.

The framework illustrates how indoor microbial communities emerge from dynamic interactions among building design, environmental conditions, human behavior and wider socio-political contexts. These interconnected factors influence microbial exposure pathways and health outcomes, highlighting the need for integrated, systems-based and socio-ecological approaches to the design, operation and regulation of healthy buildings.

Figure 2: Workshop overview and thematic focus areas.

Infographic developed for the workshop *Indoor Microbiomes and Healthy Buildings: Rethinking the Future of Indoor Health*, illustrating the principal themes explored during the event, including building design, indoor microbial ecology, environmental drivers, human behavior, health outcomes and opportunities for interdisciplinary collaboration.

Program summary

09:30–10:00 | Registration and networking

Participants arrived and engaged in informal networking over coffee.

Session 1: Welcome and objectives

10:00–10:15 | Chair: Dr Suparna Mitra

The workshop opened with an overview of its aims:

- To explore indoor microbial ecosystems
- To identify interdisciplinary knowledge gaps
- To discuss what constitutes a healthy indoor microbiome
- To examine trade-offs and unintended consequences of building interventions
- To foster future collaborations

The opening keynote by Dr Marco-Felipe King, *Designing for Health: Opportunities and Constraints in Healthy Buildings*, situated microbiome research within the broader Healthy Buildings agenda and highlighted how design decisions shape human exposure and environmental health.

Session 2: What shapes the indoor microbiome?

10:15–11:00 | Chair: Dr Michael Baidu

Roundtable discussions explored key drivers of indoor microbial communities and identified areas requiring further investigation.

Key themes

Building design and environmental drivers

Participants highlighted:

- Ventilation systems (natural versus mechanical)
- Building airtightness
- Temperature and humidity
- Building materials and furnishings
- Occupancy patterns and movement
- Pets and other biological inputs
- Water systems and biofilm formation
- Cleaning and maintenance practices

Several participants noted that highly insulated and airtight buildings may inadvertently increase condensation, dampness and mould growth if ventilation is inadequate.

Beyond individual factors, participants emphasized that these variables do not act independently but interact dynamically. For example, increased building airtightness often introduced to improve energy efficiency that can inadvertently elevate humidity levels and create microenvironments conducive to condensation and mold growth, particularly in poorly ventilated spaces.

This highlights the need for integrated design approaches in which thermal performance, ventilation and moisture control are considered simultaneously rather than in isolation.

Data and measurement needs

Participants identified several priorities:

- Integration of environmental, microbiological, behavioral and health datasets
- Development of low-cost indoor air quality and bioaerosol sensors
- Improved methods for microbial monitoring
- Personal exposure assessment
- Mathematical modelling of microbial transmission and risk

Participants further noted that current measurement approaches often fail to fully capture the complexity of indoor microbial exposure. In particular:

- Microbial counts alone may not reflect functional or pathogenic potential
- Environmental measurements are rarely integrated with behavioral data
- Links between exposure and health outcomes remain poorly characterized

This reinforces the need for multimodal data integration, combining microbiological, environmental, behavioral and clinical datasets to enable predictive modelling and risk assessment.

Areas underexplored at Leeds

Key opportunities included:

- Indoor microbiome ecology
- Antimicrobial resistance (AMR) within built environments
- Bioaerosol monitoring
- Links between indoor environmental quality and health inequalities
- Industry partnerships and real-world implementation studies

Participants agreed that Leeds is well positioned to lead interdisciplinary research in this area, particularly by leveraging existing strengths in data science, civil engineering and microbiome research, alongside access to real-world living environments for pilot studies.

Collectively, these findings indicate that indoor microbial environments are shaped by interdependent physical, environmental and behavioural factors, suggesting that interventions targeting single variables are unlikely to be sufficient, reinforcing the need for integrated and multidisciplinary approaches.

Session 3: Built environment as a microbial ecosystem

11:20–12:25 | Chair: Dr Paula Avello

Invited talks

Prof David Pearce

Functional associations and resilience in microbial communities

Prof Pearce presented evidence suggesting that geographically diverse households share a common "core home microbiome" despite differences in location and occupancy. His work highlighted the importance of microbial functional resilience and suggested that ecosystem function may remain stable even when microbial composition changes. Discussions focused on how resilience concepts from ecological systems could be applied to healthy building design.

These findings suggest that indoor microbial ecosystems may exhibit functional redundancy, whereby ecosystem processes remain stable even when species composition varies. This has important implications for defining “healthy” environments, shifting the focus from taxonomic composition towards functional resilience and stability.

Dr Ana Pitol

Understanding pathogen transmission in indoor environments

The presentation explored airborne transmission pathways, exposure risks and how building design influences infection dynamics. An analysis of risk reduction strategies was presented. SARS-CoV-2 was used as the case study.

Dr Daire Cantillon

Investigating homes for reservoirs of chronic respiratory pathogens

Discussion focused on homes as reservoirs for chronic respiratory pathogens and the implications for vulnerable populations.

Discussions highlighted that indoor environment could act not only as passive reservoirs but also as active sites of pathogen amplification and transmission, particularly through aerosolized pathways and water systems. Case examples and related discussions emphasized the role of:

- biofilm formation in plumbing systems
- aerosol generation from sinks, toilets and hand dryers
- environmental disturbances (e.g., flooding) reintroducing microbial contaminants into indoor air

Participants also raised concerns about antimicrobial resistance (AMR) in built environments, noting that sub-lethal exposures to cleaning agents and antimicrobials may contribute to the selection of resistance.

Dr Lia Chatzidiakou

Developing fast screening algorithms to detect mold risk in large datasets

This presentation demonstrated how data-driven approaches provide a pathway for identifying mold risks at scale and supporting proactive building management.

These approaches highlight the potential of data-driven, scalable tools to shift from reactive to proactive building management, enabling early risk identification and supporting targeted interventions in housing and public buildings.

Collectively, these presentations reinforce a conceptual shift towards viewing buildings as active microbial landscapes, where design and infrastructure decisions directly shape exposure pathways and health risks. In this framing, buildings function as active mediators of microbial exposure, rather than passive environments.

Lunch and ECR poster session

12:25–13:30

Early Career Researchers showcased their work through poster presentations, creating valuable opportunities for networking and interdisciplinary exchange.

Session 4: Defining health and identifying tensions

13:30–15:00 | Chair: Dr Hema Viswambharan

Discussion topic 1:

What defines a healthy indoor microbiome?

Participants debated whether healthy indoor microbiomes should be defined by:

- Diversity

- Stability
- Functional traits
- Pathogen suppression
- Environmental resilience
- Response to chemical exposures

There was broad agreement that "healthy" should not simply mean "sterile". Instead, healthy environments may support beneficial microbial interactions while limiting pathogen risks.

Several participants emphasized:

- Environmental dysbiosis
- Beneficial microbial exposure
- Indoor plants and ecosystem services
- Probiotic ventilation concepts
- The relationship between microbial diversity and immune development

Discussions converged on the view that “healthy” indoor microbiomes cannot be defined by a single metric. Instead, they represent a multidimensional construct that incorporates ecological, functional and health-related parameters.

Participants emphasized that exposure to a diverse range of microorganisms may play a role in immune development and resilience, particularly when contrasted with overly sterile environments.

Related concepts discussed included:

- Probiotic approaches to ventilation and microbial exposure
- The role of environmental microbiota in reducing allergic and inflammatory responses
- The influence of lifestyle and built environment on microbial exposure patterns

Discussion topic 2:

Trade-offs and unintended consequences

A central outcome of the workshop was the identification of fundamental tensions that currently underpin healthy building design and policy. These tensions are not easily resolved but must be explicitly navigated.

A recurring theme was the need to explicitly balance competing priorities, often resulting in unavoidable trade-offs:

Trade-off	**Key discussion points**
Infection prevention vs ecological balance	Excessive sterilization may disrupt beneficial microbial communities
Energy efficiency vs ventilation	Net-zero goals may conflict with healthy ventilation rates
Intensive cleaning vs microbial resilience	Chemical cleaning can alter indoor microbial ecosystems
Sustainability vs chemical burden	Building interventions may introduce unintended environmental impacts

These tensions highlight the need for multi-objective optimization frameworks capable of balancing health, sustainability and ecological considerations simultaneously.

Participants also highlighted:

- Hospital microbiomes
- Antibiotic-resistant microorganisms in buildings
- Sub-lethal antimicrobial exposures
- Risks associated with water systems and biofilms
- Behavioral factors such as toilet lid use and hand dryer practices

Participants stressed that these trade-offs are often implicit in current policy and design decisions yet are rarely addressed explicitly. For example, building decarbonization strategies may prioritize airtightness without adequately considering ventilation requirements, potentially exacerbating indoor air quality issues.

This highlights the need for decision-making frameworks that explicitly evaluate competing objectives, rather than optimizing for single outcomes.

Additional behavioral, societal and contextual considerations

Discussions also emphasized that behavioral and environmental decisions are shaped not only by knowledge but by social context, infrastructure and constraints, highlighting an often-underexplored dimension of indoor environmental health. For example, while natural ventilation (e.g. opening windows) is frequently promoted as a simple intervention, participants noted that this is not universally feasible. Occupants of basements, high-density flats, or transport environments such as the London Underground often lack access to operable windows, while in colder climates or seasons, there may be strong resistance to opening windows due to thermal discomfort and energy concerns. This led to the notion of a "**privilege of ventilation**", where the ability to control indoor environments is unevenly distributed and intertwined with socio-economic status and building infrastructure.

Discussions further highlighted tensions between ventilation, energy efficiency and sustainability, noting that opening windows in heated or conditioned spaces may conflict with net-zero objectives, particularly in public transport or large shared environments. Similarly, the interaction between ventilation and cleaning practices was discussed, particularly in healthcare settings, where infection-prevention priorities, such as intensive cleaning during SARS and COVID-19 may influence microbial exposures and contribute to unintended consequences, including chemical burden and antimicrobial resistance.

Behavioral aspects extended beyond building operations to encompass human psychology and hygiene practices, including variability in handwashing effectiveness and perceptions of cleanliness among healthcare professionals. These comportments can significantly influence microbial transmission pathways but are rarely incorporated into building design frameworks.

Finally, participants stressed the importance of context-specific definitions of healthy environments, recognizing that what is appropriate may differ across settings such as hospitals, care homes, or domestic spaces. Considerations of environmental exposure beyond buildings, including interactions with soil and outdoor microbiota, were also identified as important yet underexplored factors shaping indoor microbial communities and human health outcomes.

Cross-cutting insights

Across discussions, several cross-cutting insights emerged that cut across disciplinary perspectives and workshop sessions. These themes reflect shared conceptual shifts and highlight key priorities for future research and policy development.

- **Buildings as ecosystems, not containers** — A central insight was the need to move beyond viewing buildings as static physical structures and instead recognize them as dynamic ecological systems. Indoor environments continuously interact with occupants, materials, ventilation systems and external environmental conditions, shaping complex and evolving microbial communities. These interactions suggest that buildings actively influence microbial exposure and health outcomes, rather than simply hosting them. This perspective aligns with broader ecological and One Health frameworks and underscores the importance of systems-level approaches to building design, operation and evaluation.
- **Health ≠ sterility** — Participants consistently challenged the traditional assumption that healthy indoor environments should be sterile. Instead, discussions highlighted that excessive sterilization may disrupt beneficial microbial communities and potentially reduce resilience to environmental or immunological stressors. A more nuanced understanding of "health" is therefore required. One that considers microbial diversity, functional balance and ecological stability, alongside pathogen control. This shift has important implications for cleaning practices, ventilation strategies and the design of future indoor environments.
- **Behavior is as important as design — While building design plays a critical role in shaping indoor environments, there is particular emphasis on occupant behavior, which is equally influential**. Everyday practices such as ventilation habits, cleaning routines and hygiene behaviors can significantly alter microbial exposure pathways and environmental conditions. Importantly, these behavioral factors represent

modifiable and often low-cost intervention points, suggesting that effective strategies for improving indoor environmental health must integrate both engineering solutions and behavioral insights.

- **Data integration is a major bottleneck** — Despite advances in sensing technologies and microbiome research, participants identified a significant gap in the integration of diverse data types, including environmental measurements, microbiological data, behavioral patterns and health outcomes. Current approaches often remain fragmented, limiting the ability to develop predictive models or evidence-based interventions. Addressing this bottleneck will require interdisciplinary data frameworks, standardized metrics and collaborative platforms to enable a more holistic understanding of indoor environments and their health impacts.

Collectively, these insights reinforce the need for integrated, systems-based approaches that bridge microbiology, engineering, behavioral science and policy to define and deliver truly healthy indoor environments.

Session 5: Priorities and next steps

15:30–16:20 | Chair: Dr Suparna Mitra

Priority research areas

Participants identified several priority topics:

1. Development of healthy indoor microbiome indicators
2. Integration of microbiome science into healthy building standards
3. Indoor antimicrobial resistance ecology
4. Ventilation–microbiome interactions
5. Links between environmental exposures and vulnerable populations
6. Data integration across disciplines

Across discussions, there was a strong emphasis on the need to move towards standardized frameworks and indicators for healthy indoor microbiomes, which could support both research comparability and policy translation.

Potential pilot projects

Suggested future projects included:

- Indoor microbiome monitoring across building types
- Bioaerosol surveillance systems
- Indoor AMR mapping
- Ventilation and microbial exposure studies
- Occupant behaviour and microbial ecosystem interactions

Leeds was identified as an ideal testbed for such pilot studies, particularly through collaborations with local housing providers, healthcare facilities and “living lab” environments.

Policy priorities

Participants identified:

- The absence of standardized healthy building microbiome criteria
- Challenges in balancing health and sustainability policies
- The need for stronger evidence to support policy change
- Greater integration of One Health principles into building design

Participants noted that policy development is currently constrained by limited evidence linking indoor microbiomes directly to health outcomes. Strengthening this evidence base was identified as critical for influencing:

- Building regulations
- Housing standards
- Public health guidance

Participants recognised that policy change, although challenging, may offer one of the most impactful routes for improving indoor environmental health.

- Current building regulations often prioritize energy efficiency without fully accounting for indoor air quality and microbial dynamics.
- There is a critical absence of microbiome-informed standards in building design frameworks.
- Evidence linking indoor microbiomes to health outcomes is still emerging, limiting policy translation.

Future directions

Across discussions, participants identified a clear need to move beyond conceptual debates towards coordinated research, implementation and policy action. Priorities included the development of indicators for healthy indoor microbiomes, improved understanding of ventilation–microbiome interactions, indoor antimicrobial resistance ecology and the integration of environmental, microbiological, behavioral and health data. Participants also highlighted opportunities for pilot studies in real-world settings and emphasised the importance of generating evidence capable of informing future building standards, public health guidance and microbiome-informed design frameworks.

Key conclusions

Discussions across the workshop converged on several overarching conclusions. First, buildings should be viewed as dynamic socio-ecological systems in which microbial communities emerge through interactions between building design, environmental conditions and human behavior. Second, healthy indoor environments cannot be defined solely by the absence of microorganisms; rather, health should be considered in terms of ecological resilience, functional stability and controlled pathogen risk. Participants also highlighted the need to explicitly address trade-offs between infection prevention, sustainability, energy efficiency and microbial ecology. Addressing these challenges will require closer integration across microbiology, engineering, architecture, public health, behavioral science and policy. Collectively, these discussions identified indoor microbiomes as a strategically important emerging area for interdisciplinary research, with considerable opportunities for future collaboration, pilot studies and policy translation at Leeds and beyond.

The University of Leeds is ideal testbed to contribute to this emerging field through its interdisciplinary expertise, access to real-world living environments and strong links to public health and policy communities. These strengths provide a strong foundation for developing integrated research frameworks, pilot studies and translational programs focused on healthy indoor microbiomes.

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The workshop has established a strong foundation for future collaborations, pilot studies, funding applications and scholarly outputs exploring the role of indoor microbiomes in shaping healthy, sustainable and resilient buildings.